

## Implications of modes of star formation for the overall dynamics of galactic disks

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**Abstract.** One of the present concepts for the onset of massive star formation is the Kennicutt criterion. This relates the onset of massive star formation to a general gravitational instability of the gas disks of spiral galaxies. It is often overlooked, however that such gravitational instabilities of the gas disks have severe implications for the overall stability of the gas *and* star disks of spiral galaxies. I show by numerical simulations of the evolution of a combined gas and star disk that the violation of the stability condition induces violent dynamical evolution of the combined system. In particular the star disk heats up on time scales less than a Gyr to unrealistic high values of the Toomre stability parameter  $Q$ . The morphologies of both the star and gas disk resemble then no longer observed morphologies of spiral galaxies. Star formation of stars on low velocity dispersion orbits would lead to dynamical cooling of the disks to more realistic states. However, the required star formation rate is extremely high.

### 1. Massive star formation and disk stability

In an influential study Kennicutt (1989) has introduced the concept that massive star formation in spiral galaxies is related to a general gravitational instability of the gas disks of the galaxies. He demonstrated for a sample of Sc galaxies that the inner parts of the disks with massive star formation, which is observed in the form of numerous HII regions, have sharp outer radial boundaries, which coincide with the threshold of gravitational instability of the gas disks. Doubts about this concept were raised by Ferguson et al. (1996, 1998). They have shown that this transition is not as sharp as claimed by Kennicutt (1989), because they detected HII regions also in the outer parts of the disks of some of the galaxies in Kennicutt's sample. Furthermore they have argued that the gas disk of the prototype galaxy of the sample, NGC 6946, might not have reached the threshold of instability at all.

It is the aim of the present paper to point out implications of the concept of gravitational instability of the gaseous components of galactic disks for the overall stability of galactic disks.

Since the pioneering works of Safronov (1963) and Toomre (1964) there is a rich literature on disk stability which cannot be reviewed here in its entirety, but I recall only the basic principles. The gravitational stability of rotating, self

gravitating disks is regulated by two effects. First there is the well known Jeans instability, which implies that perturbations of the disks with scales larger than the Jeans length are dynamically unstable,

$$\lambda > \lambda_J = \frac{\sigma^2}{G\Sigma}, \quad (1)$$

where  $\sigma$  denotes the turbulent velocity dispersion in the case of a gas disk, or the stellar velocity dispersion in case of a star disk.  $\Sigma$  denotes the surface density of the disk and  $G$  is the constant of gravity. In a rotating disk, however, there is an upper limit to the scales on which perturbations can grow. When a patch of a disk shrinks, its detailed angular momentum referred to the center of the patch is conserved. This leads to additional centrifugal forces tearing the patch apart, and perturbations on scales larger than

$$\lambda > \lambda_c = \frac{G\Sigma}{\Omega^2}, \quad (2)$$

where  $\Omega$  denotes the angular velocity of the disk, are suppressed. Obviously, if the upper limit is smaller than the lower limit,

$$\lambda_c < \lambda_J, \quad (3)$$

the disk is stable on all scales. If the rhs of equation (3) is divided by the lhs, the stability criterion can be expressed by a single number, the famous Toomre  $Q$  stability parameter. It is derived by searching for ring-like solutions of either the hydrodynamical, the Jeans equations or the Boltzmann equation in the case of a star disk combined with the Poisson equation in order to take account of the self-gravity of the perturbations. It can be shown that the stable solutions are separated from the unstable, growing solutions in a parameter space spanned by the radial wave lengths of the ring-like density perturbations expressed in terms of the critical wave length,  $\lambda_{\text{crit}} = 4\pi^2 G\Sigma/\kappa^2$ , and the stability parameter  $Q$ ,

$$Q = \frac{\sigma_U \kappa}{\alpha G\Sigma}, \quad (4)$$

where  $\sigma_U$  denotes the turbulent velocity dispersion of the gas or the radial stellar velocity dispersion and  $\kappa$  is the epicyclic frequency,  $\kappa = \sqrt{2}\Omega\sqrt{2 + \frac{r}{\Omega}\frac{d\Omega}{dr}}$ .  $\alpha$  is a numerical coefficient, which is equal to  $\pi$  for an isothermal gas disk and ranges between 3.6 and 3.9 for a star disk depending on the exact form of the velocity distribution (Toomre 1964, Fuchs & von Linden 1998). This is illustrated in Fig. 1 for the simplest case of an isothermal gas disk. The line separating the stable from the unstable solutions is given by (cf. Binney & Tremaine 1987)

$$1 = \frac{\lambda_{\text{crit}}}{|\lambda|} \frac{1}{1 + \frac{Q^2}{4} \left(\frac{\lambda_{\text{crit}}}{\lambda}\right)^2}. \quad (5)$$

As can be seen from from Fig. 1 the disk is stable on all scales, if

$$Q \geq 1. \quad (6)$$

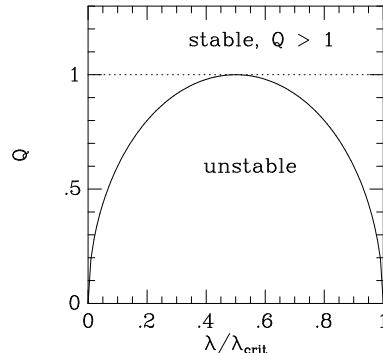


Figure 1. Separation of unstable from stable ring-like density perturbations of an isothermal gas disk in the parameter space spanned by the radial wave lengths  $\lambda$  of the density perturbations and the dimensionless  $Q$  stability parameter. The wave lengths are expressed in terms of the critical wave length  $\lambda_{\text{crit}}$

The criterion for stability becomes more complicated, if the disk consists of more than one component (Biermann 1975, Jog & Solomon 1984, Romeo 1992, Elmegreen 1995, Fuchs & von Linden 1998). I shall not go here through a mathematical derivation, but illustrate the main effect by a ‘Gedanken’-experiment. Suppose one splits a disk into two equal halves, which means according to their definitions that  $\Sigma_{1,2} = \frac{1}{2}\Sigma$ ,  $\lambda_{\text{crit } 1,2} = \frac{1}{2}\lambda_{\text{crit}}$ , and  $Q_{1,2} = 2Q$ . The surface separating stable from unstable solutions is given by

$$\begin{aligned} 1 &= \frac{\lambda_{\text{crit } 1}}{|\lambda|} \frac{1}{1 + \frac{Q_1^2}{4} \left( \frac{\lambda_{\text{crit } 1}}{\lambda} \right)^2} + \frac{\lambda_{\text{crit } 2}}{|\lambda|} \frac{1}{1 + \frac{Q_2^2}{4} \left( \frac{\lambda_{\text{crit } 2}}{\lambda} \right)^2} \\ &= \frac{2}{2} \frac{\lambda_{\text{crit}}}{|\lambda|} \frac{1}{1 + \frac{(2Q)^2}{4} \left( \frac{\lambda_{\text{crit}}}{2\lambda} \right)^2} = \frac{\lambda_{\text{crit}}}{|\lambda|} \frac{1}{1 + \frac{Q^2}{4} \left( \frac{\lambda_{\text{crit}}}{\lambda} \right)^2}. \end{aligned} \quad (7)$$

Thus, if for example  $Q = 1$ , the two components with  $Q = 2$  would be deemed rather stable, whereas the compound disk is on the brink of instability. This means in particular for a galactic disk with a star and gas disk that only

$$Q_* > 1 \quad \text{and} \quad Q_g > 1 \quad (8)$$

ensures dynamical stability. The reverse is also true: if one of the subsystems is unstable, the entire disk is dynamically unstable. This is in my view a worrying aspect of the concept of Kennicutt (1989) of dynamically unstable gas disks.

## 2. The prototype Sc galaxy NGC 6946

NGC 6946 has been studied in great detail. The radial distributions of atomic and molecular hydrogen, the radial optical surface brightness profile and estimates of the radial variation of the star formation rate as deduced from  $H_\alpha$

observations can be found in Tacconi & Young (1986). In the following I have converted densities of molecular hydrogen to the CO-to-H<sub>2</sub> conversion factor of Dame (1993). The rotation curve of NGC 6946 has been observed by Carignan et al. (1990), who also provide a mass model comprising a disk and a dark halo component. All the data are summarized in Table 1. The gas densities have multiplied by a factor of 1.4 in order to take account of the heavy elements. In order to determine the  $Q$  parameters estimates of the velocity dispersions are required. For the interstellar gas I assume following Kennicutt (1989) the ubiquitously found value of 6 km/s (Dickey et al. 1990). Kamphuis & Sancisi (1993) derive from their HI observations of NGC 6946 a velocity dispersion of the HI gas of about 13 km/s in the regions of the optical disk ( $R_{25} = 16$  kpc), which drops to 6 km/s outside the optical disk. Ferguson et al. (1998) have pointed out that, if the higher value is used to determine the stability parameter,  $Q_g$  does not drop below the threshold of instability. However, within about half the optical radius the interstellar gas is dominated by molecular hydrogen and the velocity dispersion of molecular clouds is typically 5 km/s (Gammie, Ostriker, & Jog 1991). I have thus chosen the velocity dispersions given in Table 1. The radial stellar velocity dispersions are not known, but can be estimated from the vertical hydrostatic equilibrium condition of the disk and assumptions about the form of the velocity ellipsoid as explained in Fuchs & von Linden (1998). The resulting stability parameters including corrections for the finite thickness of the disk are shown in Table 1. As can be seen from Table 1 there is a distinct drop

Table 1. Radial variation of stability parameters of the disk of NGC 6946 ( $d=10$  Mpc).

R	$\Sigma_*$	$\kappa$	$\sigma_{U*}$	$Q_*$	$\Sigma_g$	$\sigma_g$	$Q_g$	$Q_{g,min}$
5	133	50	114	2.5	38	6	0.6	0.9
10	55	23	89	2.2	21	6	0.5	1.1
12	38	20	76	2.3	17	6	0.5	1.1
14	27	17	66	2.4	14	6	0.5	1.1
16	19	15	52	2.3	6	6	1.0	1.0
18	13	13	44	2.6	5	6	1.1	1.0
20	9	12	39	3.0	5	6	1.0	1.0
kpc	$\frac{M_\odot}{pc^2}$	$\frac{km\,s^{-1}}{kpc}$	$km\,s^{-1}$		$\frac{M_\odot}{pc^2}$	$km\,s^{-1}$		

of the stability parameter of the gas disk below 1 at  $R = 16$  kpc, which coincides with the outer boundary of the HII region disk. I conclude from this discussion like Kennicutt (1989) that the massive star forming disk of NGC 6946 is indeed dynamically unstable.

### 3. Numerical Simulations

In order to follow the onset of instability into the non-linear regime I have run together with S. von Linden numerical simulations of the evolution of an unstable gas disk embedded in a star disk. The code, originally developed by F. Combes and collaborators, implements a two-dimensional star disk ( $N_* = 38\,000$ ) in which interstellar gas clouds are embedded ( $N_c \leq 38\,000$ ). The composite disk is

surrounded by rigid bulge and dark halo potentials. The gravitational potential of the star disk is calculated by a standard particle–mesh scheme and the inelastic encounters of the gas clouds is simulated by an elaborate cloud–in–cell scheme, which maintains by coalescence and fragmentation a steady mass spectrum of the clouds. Details of the simulations are described in Fuchs & von Linden (1998). The composite disk was set up initially axisymmetrically, and the  $Q$  parameters of the stars and the gas were initially  $Q_* \approx 2$  and  $Q_g \approx 0.5$ , respectively. Thus the composite disk was set up dynamically unstable and resembles in this the inner parts of the Sc galaxies from Kennicutt’s sample. The next steps of

Figure 2. cf. Fig. 7 of Fuchs & von Linden (1998)

Dynamical evolution of the star and gas disks. On the left–hand side of each panel 19 000 out of 38 000 stars and on the right–hand side of each panel 19 000 out of 38 000 interstellar gas clouds are plotted at consecutive time intervals. The time is indicated on the left in units of  $10^7$  yrs. The spatial size is indicated at the bottom by a bar of 10 kpc length.

the evolution of the disk are shown in Fig. 2. As expected ring–like density perturbations appear immediately in the gas disk. The wave lengths of the perturbations are of the order of the critical wave length of the gas disk, about 2 kpc at  $R = 10$  kpc. The rings fragment into lumps with masses in the range of  $10^4$  to  $10^7 M_\odot$ . These agglomerates are so heavy that the star disk responds to them by induced, ‘swing amplified’ spiral structures (Toomre 1981). The potential troughs of the star disk, on the other hand, begin to trap much of the interstellar gas, and during their further evolution both the star and gas disks undergo rather synchronous, repetitive cycles of swing amplified spiral perturbations. After  $5 \cdot 10^8$  yrs the star disk gets heated up dynamically by the spiral activity so much that hardly any non–axisymmetric structure is any longer possible in the disk. In the gas disk, however, there is still a lot of spiral activity. Since the star disk has become dynamically inactive, the critical wave lengths of the spiral structures are much smaller, which leads to a flocculent appearance of the disk.

#### 4. Discussion

The numerical simulations show that the disks of Sc galaxies like NGC 6946 are in a highly peculiar dynamical state. The reaction of the star disks to dynamically unstable gas disks is so fierce that they become dynamically hot within less than a Gyr. On the other hand, Toomre (1990) has argued that Sc galaxies must have star disks, which are dynamically active, because otherwise their morphological appearance would be quite different from what is observed. This can be clearly seen in Fig. 2, when one compares the frames corresponding to, say,  $1.4 \cdot 10^8$  yrs and  $4.8 \cdot 10^8$  yrs with an optical image of the galaxy which is reproduced in Fig. 3. Thus the star disks in Sc galaxies must be effectively cooled dynamically by star formation of stars on low velocity dispersion orbits. The star formation rate required to cool the star disks has been estimated by Fuchs & von Linden (1998). They conclude from their numerical simulations that about 40% of the



Figure 3. Optical image of NGC 6946 (AURA/NOAO).

mass of the star disk is required per Gyr in the form of newly born stars to keep the disk in a steady dynamical state. Interestingly the presently observed star formation rate in NGC 6946 as deduced from the extinction-corrected  $H_\alpha$  surface emissivity (Devereux & Young 1993) is actually as high as the required gas consumption rate. This is in my view not a coincidence, but has to be explained by theories of the physics of star formation. On the other hand, this mode of star formation cannot be sustained over extended periods, because a galaxy like NGC 6946 is consuming at the present rate nearly its entire gas disk within a Gyr. It will switch presumably soon to a more quiescent mode of star formation like in M 33, NGC 2403, or NGC 7331, where the threshold of dynamical instability is not reached. This is quite different in young galactic disks, where the star disks are less massive and there is an ample reservoir of interstellar gas (Fuchs et al. 2001, in preparation).

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## References

- Biermann, P.L. 1975, in IAU Symp. No. 69, Dynamics of Stellar Systems, ed. M. Hayli (Dordrecht: Reidel), 321
- Binney, J., Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)
- Carignan, C., Charbonneau, P., Boulanger, F. et al. 1990 A&A, 234, 43
- Dame, T.M. 1993, in AIP Conf. Proc. 278, Back to the Galaxy, ed. S.S. Holt & F. Verter (New York: AIP), 267
- Devereux, N.A., Young, J.S. 1993, AJ, 106, 948
- Dickey, J.M., Murray Hanson, M., Helou, G. 1990, ApJ, 352, 522
- Elmegreen, B.G. 1995, MNRAS, 275, 944
- Ferguson, A.M.N., Wyse, R.F.G., Gallagher, J.S. et al. 1996, in The Interplay Between Massive Star Formation, the ISM and Galaxy Evolution, ed. D.

- Kunth, B. Guideroni, M. Heydar-Malayeri, & Trinh Xu Thuan (Gif-sur-Yvette: Edition Frontieres), 557
- Ferguson, A.M.N., Wyse, R.F.G., Gallagher, J.S. et al. 1998, *ApJ*, 506, L19
- Fuchs, B., von Linden, S. 1998 *MNRAS*, 294, 513
- Gammie, C.F., Ostriker, J.P., Jog, C. 1991, *ApJ*, 378, 565
- Jog, C., Solomon, P.M. 1984 *ApJ*, 276, 114
- Kamphuis, J., Sancisi, R. 1993, *A&A*, 273, L31
- Kennicutt, R.C. 1989, *ApJ*, 344, 685
- Romeo, A.B. 1992, *MNRAS*, 256, 307
- Safronov, V.S. 1960, *Ann. d'Astrophys.*, 23, 979
- Tacconi, L.J., Young, J.S. 1986, *ApJ*, 308, 600
- Toomre, A. 1964, *ApJ*, 139, 1217
- Toomre, A. 1981, in *The Structure and Evolution of Normal Galaxies*, ed. S.M. Fall & D. Lynden-Bell (Cambridge: Cambridge Univ. Press), 111
- Toomre, A. 1990, in *Dynamics and Interactions of Galaxies*, ed. R. Wielen (Berlin: Springer), 292